

# The meteoroid hazard for space navigation

Luigi Foschini

Istituto FISBAT - CNR

Via Gobetti 101, I-40129 Bologna, Italy

E-mail: L.Foschini@fisbat.bo.cnr.it

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## Abstract

Thanks to post-flight analyses of several artificial satellites carried out during last years, the meteoroids hazard for space navigation and in-orbit satellites permanence is now clear. Even if catastrophic impact is a rare event, high meteoroids fluxes can erode and weaken the satellite or space station main structures. However, the main danger seems to be the impact-generated plasma, which can produce electromagnetic interferences, disturbing the on-board electronics.

**PACS-96.50.Kr** Meteors and meteoroids.

**PACS-95.40.+s** Artificial Earth satellites.

# 1 Introduction

Till now, it was a common idea that space debris were the main threat for spacecrafts. This hypothesis finds its pillar in a paper by Lurance and Brownlee (1986). The work was the result of the *Solar Max Satellite* post-flight analysis, from which was evident that space debris flux was several hundred times higher than natural meteoroids flux.

However, during last years emerge some facts that claim for a different reality. During 1993 Perseids maximum, Beech and Brown (1993) launched an alarm, because they noted that impact probabilities with *Hubble Space Telescope* sized objects, were low, but not negligible. Really, on the night of August 12, 1993, astronauts onboard the *Mir* Space Station reported audible meteoroids impacts and, then, it was verified that *Mir* experienced about 2000 hits during 24 hours and solar panels were hardly damaged (Beech *et al.*, 1995). In the same night, the ESA (*European Space Agency*) lost the control of *Olympus* telecommunication satellite. The following investigations made clear that the failure was probably caused by an impact with a Perseid meteoroid (Caswell *et al.*, 1995).

The satellites LDEF (*Long Duration Exposure Facility*) and EURECA (*EUropean REtrievable CArrier*) take the lion's share in these studies. Post-flight analyses on these satellites drastically rescaled the theories of Lurance and Brownlee on the space debris danger. McDonnell *et al.* (1997b) showed that the error in the paper of Lurance and Brownlee was due to the use of a non correct formula for transformation from crater dimension to particle mass. Then, this scientists group elaborated a new formula, by using laboratory simulations (Gardner *et al.*, 1997). New fluxes estimates, based on data collected on EURECA and LDEF, showed that, at micrometer dimensions and 500 km altitude, debris population is not dominant as previously thought (McDonnell *et al.*, 1997b). Really, above 30  $\mu\text{m}$  ballistic limit meteoroids dominates, while, for thickness between 4 and 5  $\mu\text{m}$ , 18% only of impacts are due to interplanetary matter. Moreover, the debris flux does not change appreciably in the 30  $\mu\text{m}$  size regime over the period 1980-1994, owing to atmospheric drag.

It is then very important to know the distribution and dynamics of interplanetary matter, in order to properly plan satellite orbits and space probes courses.

## 2 Distribution and dynamics of interplanetary matter

In interplanetary space, there are great matter quantities, coming from disruption of asteroids and comets. The mass range is very wide<sup>1</sup> and is observable by using several techniques: visual, radar, *in situ* and others. Crossed references among data obtained by these techniques are full of difficulties, but not impossible (Ceplecha, 1992; Foschini, 1997).

Interplanetary matter is subjected to gravitational fields of Sun and planets. In a certain sense, it is possible to say that planets are the “road-sweeper” of the Solar System, because they collect all these particles that are in their neighbourhood for a sufficient time, making some gaps in meteoroids spatial distribution (Öpik, 1951; see also the figure at p. 240 in Lindblad, 1987). On the other hand, the solar radiation pressure, due to the momentum carried by solar photons, pushes meteoroids toward outer space. In a heliocentric reference frame, let  $\vec{r}$  be the radial unit vector and let  $\vec{\theta}$  be the unit vector normal to  $\vec{r}$  in the orbit plane; the meteoroid speed is then:

$$\vec{v} = \dot{r}\vec{r} + r\dot{\theta}\vec{\theta} \quad (1)$$

and the radiation force can be written as:

$$m\dot{\vec{v}} \simeq Q_{pr}\left(\frac{SA}{c}\right) \left[ \left(1 - \frac{2\dot{r}}{c}\right)\vec{r} - \left(\frac{r\dot{\theta}}{c}\right)\vec{\theta} \right] \quad (2)$$

where  $SA$  is the total amount of energy intercepted, per second, from a radiation beam of integrated flux density  $S$  by a stationary, perfectly absorbing meteoroid of cross section  $A$  and  $Q_{pr}$  is the radiation pressure coefficient, proportional to the total momentum withdrawn from the beam (Burns, 1987). Usually, the velocity-dependent part of (2) is called *Poynting-Robertson effect*, while the radial term is simply called *radiation pressure*, even if, as Burns (1987) wrote, there are also other accepted customs.

There is another non-gravitational force, the so-called *Yarkovsky effect*. This effect is connected with the name of a polish engineer who first described it in a pamphlet published in russian around 1900 (see Öpik, 1951). It is

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<sup>1</sup>Generally speaking, a ‘meteoroid’ is intended to be a cometary or asteroidal body with a mass range between  $10^{-9}$  and  $10^7$  kg, even if there is a vivid debate around this definition.

a force generated by asymmetries in the reradiated thermal energy from a rotating body exposed to Sun, because the evening hemisphere is slightly warmer than the morning one. The warmer hemisphere radiated more energy, and hence momentum, than the other hemisphere, producing a net force, which depends on rotation frequency, thermal properties and dimensions of the body, and from Sun distance (Burns, 1987). In a similar way, it is possible to speak about a “seasonal” effect, where the temperature difference between summer and winter produces a net force, which depends on polar axis orientation (Rubincam, 1995). If collisions change the rotational state of cosmic bodies, the amplitude and direction of the force due to the Yarkovsky effect change in time in a stochastic way, producing a random walk of the major semiaxis of the body orbit.

The ratio among these forces can vary according to dimensions and masses of interplanetary bodies, distributing the matter in the Solar System. Only those particles, that are in the neighbourhood of a planet for a little time thanks to Poynting-Robertson effect, can survive to the gravitational attraction (“road-sweeper” effect). The Poynting-Robertson effect become fundamental for bodies in the range from  $0.1\ \mu\text{m}$  to some centimetre (Burns, 1987). The Yarkovsky effect is dominant for larger bodies (0.1-100 m). In the asteroidal population, this effect produces an orbital major semiaxis drift, driving the delivery of meteoroids toward Earth (Farinella *et al.*, 1998).

Taking into account observations, made with several techniques, and the dynamics of the interplanetary matter, it is possible to elaborate a model, in order to know meteoroids fluxes and concentrations. Now, the starting point is the model elaborated by Grün *et al.* (1985) and regarding the interplanetary matter dynamics at 1 AU (*Astronomical Unit*) from the Sun. Throughout the model, the following characteristics of meteoroids population are considered: (1) the mean mass density is  $2500\ \text{kg/m}^3$ ; (2) the relative speed between different meteoroids, as well as the impact speed on the Moon, is 20 km/s; (3) the flux onto Earth, as well as mutual impact flux, is isotropic. Divine (1993) extended this model, taking also into account data from space probes (Pioneer 10 and 11, Ulysses, Galileo and Helios-1), and found five populations of meteoroids, each named for a distinctive characteristic of their orbital distributions and of their mass. Taylor and McBride (1997) used data recorded by *Harvard Radio Meteor Project* in order to extend the model by Grün *et al.* (1985), taking into account the anisotropies in the meteoroids environment. This radiant-resolved meteoroid model was preceded by a reanalysis and correction of speed distribution obtained from radars, which can affect

large meteoroids distribution in Divine's model (Taylor, 1995). However, Grün *et al.* (1997) recently developed a new model from the Divine's one, including the effect of radiation pressure on the meteoroids speed and considering impact directions and speeds. The new model lead to four meteoroids populations on elliptical orbits and one moving on hyperbolic orbits.

At last, it should be pointed out that other models are now available (Gor'kavyi *et al.*, 1997; Wasbauer *et al.*, 1997).

### 3 Impact probabilities

The higher risk regions are those related to meteoroid streams, that when encounter the Earth give rise to meteor showers. In these streams, the meteoroids number per volume unit can reach very high values, with geocentric speeds up to 71 km/s (Kresák, 1993; Jenniskens, 1995). By the time, it is known the last meteor storm generated during 1966 by Leonids, when a ZHR (*Zenithal Hourly Rate*) of 150,000 was recorded<sup>2</sup>. The next perihelion passage of Leonid parent body, the comet P/Tempel-Tuttle, happened on February 1998. Then a new meteor storm is expected. If it will be so, there will be a considerable hazard for artificial satellites (Beech and Brown, 1994; Foschini and Cevolani, 1997).

A rough evaluation, of the impact probability of a meteoroid with an artificial satellite, can be made assuming an uniform and constant flux intercepting an area  $A$  [m<sup>2</sup>] for a time  $t$  [s]:

$$I = nFVA t \cdot 10^{-13} \quad (3)$$

where  $V$  [km/s] is the geocentric mean meteoroids speed and  $n$  [km<sup>-3</sup>] is the spatial number density of meteoroids contained, during normal conditions, into an equivalent 1000 km sized cube. During storms or outbursts, it is necessary to introduce an enhancement factor  $F$ , that for Leonids ranges from 300 to 10000 (Beech and Brown, 1994). In order to calculate the spatial number density, it is necessary to know the flux density of meteoroids  $\Phi$

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<sup>2</sup>Jenniskens (1995) rose some doubts on this ZHR evaluation, that do not find a consideration in radar data. According to Jenniskens, the correct value should be ZHR=15,000±3,000.

[ $\text{km}^{-2} \cdot \text{h}^{-1}$ ] in a specific mass range, because  $n$  is defined as (Koschack and Rendtel, 1990a, b):

$$n = \frac{\Phi}{3600V} \quad (4)$$

The flux evaluation is very difficult, because the Earth encounter a part of meteoroids only. Moreover, it must be take into account the origin of meteoroids: when the parent body is a comet, a part of the nucleus surface only is active<sup>3</sup> and, then, particles are expelled along several preferred directions, arranging themselves on slightly different orbits, even if centered along the orbit of the parent body. Furthermore, considering the forces described in the previously section, meteoroids will move along particular configurations, composed by several filaments<sup>4</sup>. The effect on radar and visual observations of these structures is that there are one or more peaks during shower activity. Generally speaking, flux evaluation are made by using visual observations and taking into account several corrective factors, in order to offset for limiting elements (Koschack and Rendtel, 1990a, b; Jenniskens, 1994; Brown and Rendtel, 1996). However, an important limit is due to maximum magnitude (+6.5), corresponding to a meteoroid of about  $10^{-5}$  kg (Jenniskens, 1994). But with radars, it is possible to reach magnitude +16, that should correspond to a mass of about  $10^{-9}$  kg (Zhou and Kelley, 1997). Other advantages are a wide collection area (for forward-scatter radars it is possible to reach some thousands of square kilometre) and the absence of weather, sunlight or moonlight limitations. However, flux evaluations are possible imposing some restrictive hypotheses only: uniformity in space and time, and the mass index constant and equal to a mean value (Foschini, 1997). Radar data allow us to make a meteoroid streams map, different from that obtained with visual observations. Nevertheless, in both cases, it is possible to deduce that catastrophic impact is a rare event, even if when there is a meteor storm (Beech and Brown, 1994; Beech *et al.*, 1995; Foschini and Cevolani, 1997). When micrometeoroids are considered the impact is not so rare: for example, there is 41% of impact probability for a space station (1000 m<sup>2</sup> area, 1 hour exposure), with a meteoroid with mass equal or greater than  $10^{-8}$  kg, if there will be a storm like 1966 Leonids (Foschini and Cevolani, 1997). Such a flux

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<sup>3</sup>For example, when the Halley comet reach the Sun, about the 3% of its surface is active.

<sup>4</sup>Some images of these structures can be found in: Beech and Brown (1994), Hughes (1995), Arter and Williams (1997).

can make serious damages to mechanical structures, particularly solar arrays and antennas, that can not be obviously shielded.

## 4 Impact-generated plasmas

The *Olympus* satellite experience, the post-flight analysis and the calculations of impact probabilities impose a revision of potential space dangers. The mechanical impact do not seems to be a risk, as shown by several cases like the *Hubble Space Telescope* (Herbert and McDonnell, 1997) and the *Mir* space station (Christiansen *et al.*, 1997). However, the *Olympus* failure is a paradigmatic example: in that case, the impact with a Perseid meteoroid could have generated electrical failures, leading to a chain reaction which culminated with an early end of the mission. According to Caswell *et al.* (1995), a gyro motor stopped, probably owing to a lack of power, and the satellite lost the reference. Following manoeuvres in order to acquire a new reference (*Emergency Sun Acquisition*) failed, probably owing to a short circuit in a capacitor of the emergency network. Even if there is not any certainty, it seems that the impact of a small meteoroid may have generated a plasma triggering discharge of charged surfaces, entering the grounded spacecraft via the umbilical.

After the *Olympus* end-of-life anomaly, other authors looked to impact-produced plasma, rather than the impact itself (Brown *et al.*, 1996; McDonnell *et al.*, 1997a). It is well known that, during an hypervelocity impact, a fraction of the projectile and target materials is evaporated and even ionized (Fechtig *et al.*, 1978). A plasma cloud is then created almost instantaneously after the impact and expands into the surrounding vacuum. McDonnell *et al.* (1997a) find an empirical formula for evaluation of charge production during an hypervelocity impact. This equation, rearranged in order to emphasize projectiles dimensions and densities, can be written as:

$$Q \simeq 3.04\delta^{1.02}r^{3.06}V^{3.48} \text{ [C]} \quad (5)$$

where  $\delta$  is the meteoroid density [kg/m<sup>3</sup>],  $r$  is the meteoroid radius [m] and  $V$  its speed [km/s].

Because of the energy range, the plasma production is related to chemical composition of meteoroid. Cometary streams, richer of low ionization

potential elements, will be more dangerous than other. The Leonid meteoroid stream results to be the most dangerous stream, even during normal condition (McDonnell *et al.*, 1997a).

The impact-produced plasma can disturb the satellite in several ways: if directly injected into circuits can destroy part of the onboard electronics (McDonnell *et al.*, 1997a); thermal forces can magnetize the neighbourhood of craters (Cerroni and Martelli, 1982); electromagnetic radiations emitted from the plasma can disturb several resources or scientific experiments on the satellite (Foschini, 1998). Even if satellites are actually submitted to several procedures for electromagnetic compatibility (EMC), meteoroid impacts call for new studies on these arguments. For example, the plasma-generated charge can deposit on near surfaces and, subsequently discharges to mass. The pulse shape will depend on electric characteristics (resistance, inductivity, capacity) of employed materials. Moreover, the pulse can disturb the onboard electronics, mainly in four ways (Audone, 1993; Foschini and Gallerani, 1993):

1. the discharge can be directly injected into a circuit;
2. the discharge can hit a nearby surface and disturb a circuit by a secondary discharge;
3. capacitive coupling between the discharge electric field and the circuit;
4. inductive coupling between the discharge magnetic field and the circuit.

If the first two modes are localized, and then depend on the impact place, the third and fourth modes can disturb distant components. However, these coupling effects are strongly non-linear and depending on circuit layout. Thus, more detailed studies can be made on specific satellite only.

## 5 Conclusions

The threat from meteoroids must be revised, taking into account experiences such as *Olympus* and experimental studies (McDonnell *et al.*, 1997a). Mechanical damages are localized, sporadically hit important parts and the catastrophic impact is an event still rare. On the other hand, if the plasma charge and current production are considered, then the risk increase and meteoroid streams, particularly those composed with low ionization potential

elements, can be dangerous even during normal conditions. More studies about electromagnetic interferences from impact-produced plasmas are required.

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